WSR-88D Receiver Noise Temperature

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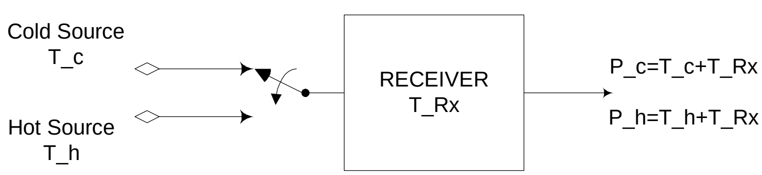
ABSTRACT

This paper shows the Noise Figure calculations for the WSR-88D receiver with ORDA installed. It shows and explains the differences with the legacy Noise Temperature. Variances with Suncheck are examined and corrected. We show the new equations and the justification for using them.

Introduction

Noise Figure and Noise Temperature show the noise added by the receiver. To measure them, we need 2 calibrated noise sources, "hot" and "cold". In the WSR-88D, the 4A25 Noise Source provides our Hot Noise Source, while the Cold Noise Source is from the antenna pointed at blue sky (defined as the antenna pointed above 5°). The exception is the non-controlling channel in a redundant system where a dummy load provides the Cold Noise Source. Figure 1 shows the basic idea. Each noise source is switched in and the power is measured at the end of the receiver. The ratio of the powers and the known temperatures gives the receiver's noise temperature from the measured noise factor, related by $T_{Rx} = 290(F-1)$. F is normally represented in dB (and known as Noise Figure), so $NF = 10\log(F)$.

The blue sky noise from the antenna differs significantly from the dummy loaded noise because they are at different Noise Temperatures. This is seen by the 2dB difference in measured noise power between blue sky and dummy load. It can also be seen when the antenna is pointed at the ground (-1°), where the noise varies from –1dB to –1.7dB higher than blue sky (on a day with ambient temperature approximately 55° F). This shows that the noise temperature of blue sky noise is significantly lower than ambient.



$$T_{Rx} = \frac{\left(T_H - \frac{P_H}{P_C} T_C\right)}{\left(\frac{P_H}{P_C} - 1\right)}$$

Figure 1

The hot noise source for the WSR-88D is a diode noise source, providing a known noise. Its output is characterized by a term known as Excess Noise Ratio (ENR), defined as:

$$ENR = 10\log\left(\frac{(T_H - 290)}{290}\right)$$

Equation 1

290K is a reference cold temperature. In the T_{Rx} equation in Figure 1, if you make T_C = 290, and then substitute ENR, you can show the equivalence of the equation to the Noise Temperature equation:

$$T_{Rx} = \frac{\left(T_H - \frac{P_H}{P_C}T_C\right)}{\left(\frac{P_H}{P_C} - 1\right)} = \frac{\left(T_H - \frac{P_H}{P_C}T_C\right) + T_C - T_C}{\left(\frac{P_H}{P_C} - 1\right)} = \frac{\left(T_H - T_C - T_C\left(\frac{P_H}{P_C} - 1\right)\right)}{\left(\frac{P_H}{P_C} - 1\right)} = \frac{\frac{T_C(T_H - T_C)}{T_C}}{\left(\frac{P_H}{P_C} - 1\right)} - T_C =$$

$$T_C\left(\frac{\frac{(T_H - T_C)}{T_C}}{\left(\frac{P_H}{P_C} - 1\right)} - 1\right) = 290\left(\frac{\frac{(T_H - 290)}{290}}{\left(\frac{P_H}{P_C} - 1\right)} - 1\right) = 290\left(\frac{10^{\frac{ENR}{10}}}{\left(\frac{P_H}{P_C} - 1\right)} - 1\right)$$

Where the Noise Temperature Equation is:

$$T_{Rx} = 290(F - 1) = 290 * \left(\left[\frac{10^{ENR/10}}{\left(P_H/P_C\right) - 1}\right] - 1\right)$$

Equation 2

Value	WSR-88D Term	Explanation
T_{Rx}	Noise Temp	Receiver Noise Temperature
ENR	ENR+Noise_Path(5)	ENR at the receiver input
P_H	Noise_{On}	Noise Power of Hot Source at Receiver Output
P_C	Noise_{Off}	Noise Power of Cold Source at Receiver Output

This is the equation used in the legacy system.

WSR-88D Noise Temperature

Receiver Configuration

There are 6 basic stages for the WSR-88D receiver when ORDA is installed, as shown in **Figure 2**. The first 2 stages show where the Noise Source is injected.

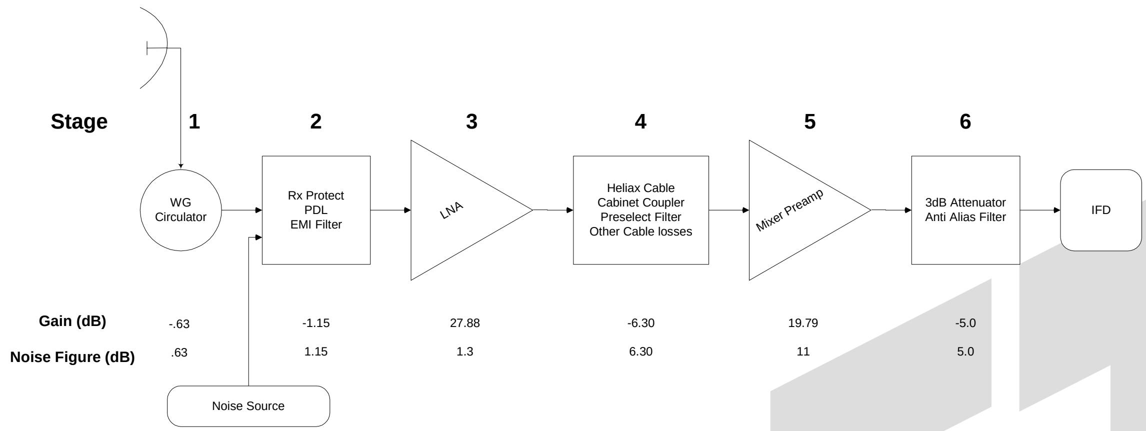


Figure 2

This is a typical heterodyne receiver with cascaded stages. The LNA is located in the front end to reduce the receiver Noise Temperature and the significance of added noise for successive components. The LNA and the losses before it dominate the Noise Temperature calculations for the WSR-88D.

Theoretical Noise Temperature

The cumulative Noise Figure for the stages themselves are calculated as follows, using the standard cascade equation for noise: $F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{F_N - 1}{G_1 G_2 G_3 \cdots G_{N-1}}$, where F and G are expressed in ratios, not dB.

Table 1

Adapt [1]	Value dB	Gain/Loss Ratio	Gain/Loss Combined	Noise Figure dB	Noise Figure Ratio		Front End Noise Factor	Antenna Noise Factor
Antenna	-0.63	0.8646	0.8646	0.6319	1.1566	Stage 1		1.16
R73 (Rx Prot)	-0.65	0.8607						
EMI Filter	-0.50	0.8913	0.7671	1.1513	1.3036	Stage 2	1.30	1.51
R74 (LNA)	27.88	613.7620	613.7620	1.3000	1.3490	Stage 3	1.76	2.03
R77 (cable)	-3.46	0.4508						
R78 (atten)	-0.59	0.8735						
R81 (filter)	-2.22	0.5992						
R82 (cable)	-0.03	0.9931	0.2344	6.3012	4.2670	Stage 4	1.77	2.04
R83 (atten)	19.79	95.2796	95.2796	11.0000	12.5893	Stage 5	1.87	2.16
R249 (filter)	-3.00	0.5012						
R250	-2.00	0.6310	0.3162	5.0000	3.1623	Stage 6	1.87	2.16
						Noise Temp	252.48	337.44

This clearly shows that the LNA dominates Noise Figure. The 2 Noise Temperatures show the difference between receiver noise starting at the Receiver Front End versus starting at the antenna feedhorn. When we measure Noise Temperature in the WSR-88D, we measure the Receiver Front End Noise Temperature because that is where we inject our Noise Source.

Measuring Noise Temperature

In the WSR-88D, we use the calibrated Noise Source to determine the Noise Temperature of the receiver from Front End to IFD. We measure the Noise Floor with the antenna pointing at blue sky and then turn on the Noise Source and measure the Noise again. The difference is used to determine Noise Temperature by the equation:

$$Noise_{Temp} = 290 * \left(\left[\frac{10^{\left(Noise_{source} + Noise\_Path_{ATTEN(5)}\right)/10}}{\left(Noise_{ON} / Noise_{current}\right) - 1} \right] - 1 \right)$$

Equation 3

where

$Noise_{Temp}$	Receiver Noise Temperature, the amount of noise added by the receiver (T_{Rx})
$Noise_{source}$	ENR from the Noise Source, referenced to 290K
$Noise\_Path_{ATTEN}(5)$	loss from the Noise Source to Front End injection, with 5dB attenuation selected on the 7-bit test attenuator
$Noise_{source} + Noise\_Path_{ATTEN(5)}$	ENR, noise power injected into the Front End (ENR_{FE})
$Noise_{ON}$	noise power measured at the IFD with the Noise Source On, the “Hot” Noise Power (P_h).
$Noise_{off}$	noise power measured with “blue sky” noise, the “Cold” Noise Power (P_C). On the non controlling channel in a redundant system, this is noise from a dummy load, close to the reference 290K.

Measurement Problems

Unfortunately, the legacy actually implemented a different equation:

$$Noise_{Temp} = 290 * \left(\left[\frac{10^{\left(Noise_{source} + Noise\_Path_{ATTEN(5)}\right)/10}}{\left(Noise_{ON} / Noise_{current}\right) - 1} \right] \right)$$ Translates to: $Noise_{Temp} = 290(F)$

Equation 4

This is missing the “- 1” in the equation, and means the legacy added 290K to all its Noise Temperature readings. This is equivalent to System Noise Temperature (as opposed to Receiver Noise Temperature) where ambient room temperature is assumed for the input Noise Temperature. System Noise Temperature includes the input noise and added receiver noise.

$Noise_{ON}$ is referenced to the Receiver Front End and $Noise_{off}$ is referenced to the antenna blue sky. This form of the equation assumes $Noise_{off}$ is 290K (see Figure 1). Our actual $Noise_{off}$ uses the noise from the antenna, and this is substantially less than 290K. This is not easily corrected with this form of the equation (ENR reference is 290K).

Receiver Noise Temperature represents the amount of noise added by the Device Under Test (DUT), and is invariant with respect to measurement technique. In legacy, a non-controlling channel of a redundant system shows a Noise Temperature approximately 220K higher than a controlling channel. The difference is that a non-controlling channel is connected to a dummy load instead of the antenna, thus giving it a reference Noise Temperature for $Noise_{off}$ of approximately 290K, making Equation 3 correct. In legacy, a non-controlling channel is given higher noise temperature alarm limits because of this difference.

In the classic Noise Temperature test, the hot and cold sources are inserted separately (see Figure 1). However, in the WSR-88D, the hot source is added to the cold source, and not separately switched. This means that, unless the hot noise source is sufficiently powerful to swamp the cold source, it affects the results. Fortunately, the hot noise source in the WSR-88D is more than 15dB above the noise floor, removing it as a significant source. This is not true for Suncheck, however, when we are pointed at the sun.

In the following paragraphs, we will examine each of these problems, and advise a solution to calculating Noise Temperature.

Reference Points

$Noise_{ON}$ is referenced to the front end, while $Noise_{off}$ is referenced to the Antenna. Therefore, one of these 2 power measurements must be corrected for this equation to show a proper Noise Temperature. The difference is 0.65dB, the waveguide loss from Antenna to Front End. Whether $Noise_{ON}$ or $Noise_{Off}$ is corrected depends on the Noise Temperature the system models. If we're modeling the entire system Noise Temperature, then we need to correct $Noise_{ON}$. Conversely, if we're modeling the Receiver Noise Temperature, we need to correct $Noise_{off}$. This paper will assume we are modeling Receiver Noise Temperature because of problems with correcting $Noise_{ON}$ and the assumptions we must make regarding T_C.

Cold Temperature Measurement

The $Noise_{off}$ in Equation 3 assumes the input Noise Temperature is 290K. This is not normally true in the WSR-88D, using antenna blue sky noise as our reference. We operate in the S band, between 2700Mhz and 3000Mhz. This makes our antenna Temperature approximately 35K when the antenna is pointed above 5° (Space Noise 4K, Atmospheric Noise 3K, Radome Loss 15K, sidelobe loss 13K), then with the feed to the Receiver Front End we add another 0.63dB, making the Noise Temperature at the Front End approximately 70K. This was done experimentally on KCRI Channel 2, using the noise level difference between Antenna and Dummy Load, as follows:

	Antenna (dBm)	Dummy Load (dBm)	Delta (dB)
Noise Level at IFD	-76.85	-74.8	2.05
Temp	T_{Ant}	290	

$$NF_{Dummy} = 10\log\left(\frac{Temp}{290}+1\right) = 10\log\left(\frac{290}{290}+1\right) = 3dB$$

$$NF_{Ant} = NF_{Dummy} - Delta = 3 - 2.05 = .95dB$$

$$T_{Ant} = 290\left(10^{\frac{NF_{Dummy}}{10}} - 1\right) = 290\left(10^{\frac{.95}{10}} - 1\right) = 71K$$

This same difference in Noise Power shows up when the antenna is pointed at the ground, varying 0.6 to 1.7dB from blue sky noise, depending on azimuth. If the antenna blue sky noise were identical to ambient, we would expect a very small delta. Pointing the antenna above 5° made no difference in the measured noise power.

Unfortunately, it isn't easy to use Equation 3 to model a different cold noise temperature reference.

Suggested Noise Temperature Calculation

To solve the problems with Noise Temperature, we need to return to an original equation for Receiver Noise Temperature, shown from Figure 1:

$$Noise_{temp} = \frac{\left(T_H - \dfrac{Noise_{on}}{Noise_{current}} T_C\right)}{\left(\dfrac{Noise_{on}}{Noise_{current}} - 1\right)}$$

Equation 5

Since we have $Noise_{on}$ and $Noise_{off}$, we only need to get T_H and T_C. These are derived as follows:
T_H is the hot temperature at the receiver front end when we turn the noise source on. It is related to ENR as shown in Equation 1. Rearranging the equation and using the ENR equation for the legacy WSR-88D, we have:

$$T_H = 290\left(10^{\left(\frac{Noise_{source} + Noise\_Path_{ATTEN(5)}}{10}\right)} + 1\right)$$

As shown above, for the antenna:

$$T_C \approx 70K$$

For a non-controlling channel in a redundant system:

$$T_C \approx 290K$$

Recommendations

We recommend that Noise Temperature be calculated using Equation 5, with T_C = 70K for antenna and 290K for dummy load (non-controlling channel of a redundant system). We would still like to gather data on a system with the EMI filter in a normal configuration, i.e. the EMI filter between the Receiver Protector and the LNA. This should only make a difference in the T_C, probably in the order of 10-15K.

Noise Temperature Calibration

We can actually measure T_C of the antenna, using known quantities. The test procedure consists of replacing the antenna with a known cold source (a dummy loaded mode adapter) to determine the receiver noise temperature, and then calculating T_C from the known quantities. Combining the equations, we get the following single calculation to determine T_C.

$$T_C = \frac{T_H\left(P_C - P_R\right) - T_R\left(P_C - P_H\right)}{\left(P_H - P_R\right)}$$

Where:

T_C	Blue Sky Antenna Temperature measured at Receiver Front End
P_C	Antenna Power Level at IFD
T_R	Dummy Load Ambient Temperature in Kelvin measured at Receiver Front End
P_R	Power Level at IFD with 50Ω Termination at Receiver Front End
T_H	Temperature of Noise Source with 5dB attenuation at Receiver Front End
P_H	Power Level at IFD with Noise Source turned on and 5dB attenuation selected

The only assumption made here is that T_H is the same for Antenna or Dummy Load. This is a poor assumption only if ENR power level is not at least 10dB above Noise. At 5dB attenuation, we get over 20dB power above noise.

Suncheck

Part 2 of Suncheck uses the noise source to calculate the solar Noise Temperature input to the Receiver. This value is used to verify antenna gain. The equation used for Noise Temperature into blue sky will not work when we're pointed at the sun because the sun noise power is within 5dB of the noise source power. This means the noise source on measurement is contaminated with the sun power, since we do not switch off the antenna when we use the noise source. Fortunately, it is easy to model the hot temperature as the addition of the sun temperature and the noise source temperature.

System Data

The following data sets were taken on KCRI Channel 2 and KREX. Compared to operational systems, neither one of these systems has an EMI filter past the Receiver Protector (KCRI has an EMI filter in the waveguide, KREX has no EMI filter). The Noise Temperatures were computed using Equation 5

System	$Noise_{off}$ dBm	$Noise_{on}$ dBm	Input ENR dBm	T_C K	Equation Used	Noise Temp
KCRI Antenna	-76.8	-53.7	23.48	70	Equation 5	243
KCRI Dummy Load	-74.8	-53.9	23.48	290	Equation 3	237
KREX	-73.0	-48.7	27.00	290	Equation 3	252
KREX Noise Standard	-73.0	-50.7	25.00	290	Equation 3	253

The Noise Temperatures are remarkably consistent, and in line with expectations.

[1] NWS:EHB6, Maintenance Note 30, Attachment 1, Receiver Statistical Data